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REPORT

Hybrid-pulse coding:

experimental assessment of system as applied to video signals

No. 1969/45

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

RESEARCH DEPARTMENT

HYBRID-PULSE CODING: EXPERIMENTAL ASSESSMENT OF SYSTEM AS APPLIED TO VIDEO SIGNALS

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(EL-31)

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SUMMARY

Hybrid-pulse coding (h.p.c.m.) is a method of coding a baseband signal into a moderately wideband channel in order to improve the noise performance of signal-processing and transmission systems. A previous Research Department Report (1969/40) describes the principles of this coding system in some detail.

An experimental feasibility study has been made of the application of h.p.c.m. to the transmission of 625-line 5·5 MHz video signals over poor r.f. circuits. The present report briefly outlines the instrumentation of the experimental equipment and also describes the results of tests made to assess both objectively and subjectively the noise performance of the system.

1. INTRODUCTION

Hybrid-pulse code modulation is a variant of multilevel p.c.m. which can improve the noise performance of channels used for signal processing and transmission in those cases where the signal bandwidth can be expanded by a factor of only two or three times. A previous Research Department Report (No. 1969/40)[1] has made a detailed theoretical assessment of this coding system with particular reference to hybrid-coding 625-line PAL colour signals for noise reduction over poor quality r.f. transmission links. Experimental equipment has been made in order to test the practical feasibility of this application. The present report briefly outlines the instrumental requirements and design of the experimental system and then describes the results of tests made to assess its noise performance both objectively and subjectively as well as the overall degradation of h.p.c.m. colour pictures.

2. THE EXPERIMENTAL SYSTEM

2.1. Basic System Requirements

It became clear from the theoretical investigation[1] that the only system which merited practical study was twin-pulse h.p.c.m. in which the digital and analogue signal components each occupy a bandwidth equal to the original base-bandwidth (f_0 = 5·5 MHz). Quantisation for 5-level coding was adopted because this index offers the largest signal-to-noise improvement (≃14 dB) consistent with an acceptable digital error rate (≃ one per frame); this result can be achieved theoretically with a channel signal-to-noise ratio of 34 dB (peak video-to-unweighted r.m.s. noise). The nominal total transmission bandwidth of this system is equal to $2f_0$(= 11 MHz) but because of the practical limitations of baseband filters the sampling frequency has to be somewhat greater than $2f_0$. For the purpose of the experiments simultaneous pulse transmission was chosen, but the instrumentation was such that the performance of the equivalent t.d.m. system could also be inferred from it. We shall not be concerned here with design details as these are discussed elsewhere.[2]

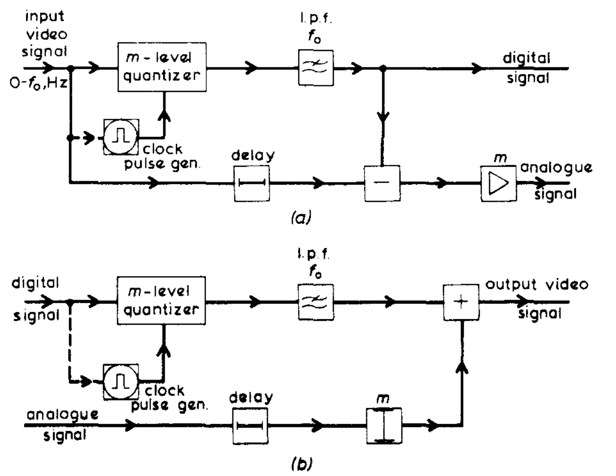

Fig. 1 - Simplified block diagram of experimental system
(*a*) sending terminal : hybrid coder
(*b*) receiving terminal : hybrid decoder

Fig. 1 shows the basic arrangement at the sending and receiving terminals for the simultaneous twin-pulse system having a transmission bandwidth f_0(= 5·5 MHz) in each channel. The operation of this circuit is straightforward. The digital signal is transmitted as a 5-level quantized signal (i.e. m = 5, Fig. 1)* band-limited to 5·5 MHz and the analogue signal as the difference between the instantaneous input video and digital signals amplified by 14 dB; the analogue delay unit is required because the quantizer and low-pass filter retard the digital signal. At the receiving

* Quantizing levels are numbered 0,1,2, ... m and it is assumed that there are m threshold detectors.

terminal the digital signal is regenerated in a quantizer to remove noise from the multilevel component; the output video signal is reconstructed by adding the regenerated digital signal, again band-limited to 5·5 MHz, to the received (and delayed) analogue signal attenuated by 14 dB.

Quantizers in systems of the type shown in Fig. 1 normally incorporate time-sampling (and holding) because it allows the threshold detectors to make level decisions unambiguously. Apart from instrumental convenience, however, time-sampling is essential if the full noise advantage is to be obtained from channels of restricted bandwidth. If some reduction in noise advantage can be permitted then time-sampling is not fundamentally essential, and indeed, if it is omitted the quantizers at the sending and receiving terminals need not be synchronized. In t.d.m. systems there must, of course, be sampling and synchronization processes in order to effect the pulse sequencing operation. The experimental hybrid coder and decoder in Figs. 1(*a*) and (*b*) employed quantizers incorporating time-samplers and most of the tests were carried out with a third channel or 'cheat wire' providing clock synchronization. In principle, clock synchronization can be obtained by locking the coder clock phase to the colour sub-carrier of the input video signal and then deriving clock phase at the decoder from the received quantized video signal. Although this method, indicated in Fig. 1 by dotted connections, was not used in the experimental tests, it was later shown that codec synchronization is feasible if the third harmonic of the colour burst ($3f_{sc} \simeq 13{\cdot}3$ MHz) is employed.

The synchronizing waveform of a composite video signal is already quantized so that unless the sync pulses contain other information, such as binary p.c.m. sound,[3] for example, there is no reason why they should not be truncated and specified by no more than a single digital level; the full synchronizing waveform can be easily reconstructed at the receiving terminal. The advantage of sending truncated sync pulses is that the picture component can then occupy more of the available modulation depth in the channel, thus providing a greater noise improvement. Fig. 2 shows the arrangement used in the experimental equipment; the 625-line video signal is positioned in relation to the 5 quantizing levels so that blanking level is placed halfway between levels 0 and 1 while the colour burst signal is symmetrically quantized. With this arrangement, the noise improvement is increased by about 2 dB above that provided by an h.p.c.m. system which codes the entire composite video waveform.

2.2. Special Problems

The main problems requiring special attention in the instrumentation of h.p.c.m. arise as a result of splitting the wanted signal into two additive components. It is essential to preserve the complementary nature of these components to a high degree of accuracy in order that the original signal can be satisfactorily reconstructed at the receiving terminal. Since the characteristics of the transmission channel will normally depart from those required for the accurate transmission of $\sin x/x$ pulses, some form of supplementary equalization must be introduced for the purpose of hybrid decoding.

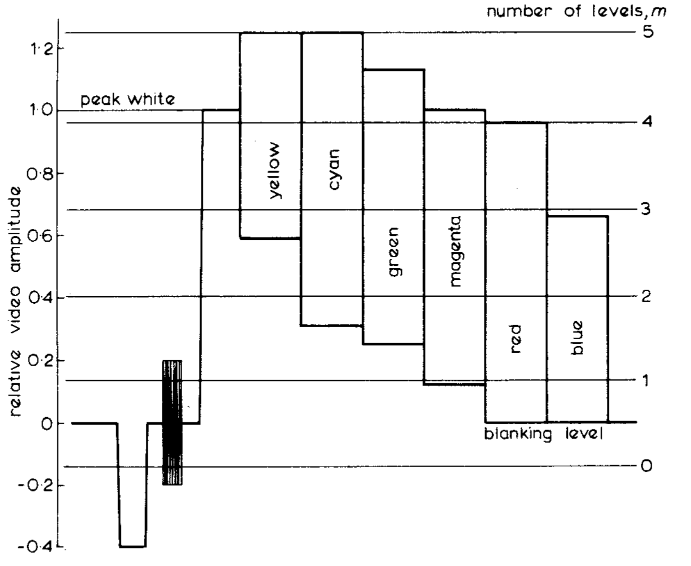

Fig. 2 - Position of quantizing levels in 625-line television signal: 5-level system showing colour bars

Careful design is required for certain units in the hybrid coder and decoder. The sampling quantizers (Fig. 1) with their associated low-pass filters and sample-and-hold equalizers should be as nearly identical as possible, this particularly includes the phasing of the samplers which must be accurately synchronized. At the sending terminal the accuracy of subtraction is obviously of paramount importance. Although the operation may be performed before or after filtering the quantized signal, it is an advantage to subtract at video frequencies in order to save using a second (matched) filter for the analogue channel, a minor disadvantage is that the length of the required analogue delay is increased. At the receiving terminal the relative delay between the analogue signal and the filtered quantizer output must be finely controlled to effect good signal reconstruction. Any outstanding linear errors in the output signal can be removed by post-decoder amplitude and phase equalization.

3. PERFORMANCE OF EXPERIMENTAL SYSTEM

3.1. Experimental Arrangement

The performance of the twin-pulse 5-level h.p.c.m. system for 625-line television briefly described in Section 2.1 was determined by objective and subjective tests. A simplified block diagram of the experimental arrangements used is given in Fig. 3. The h.p.c.m. system employed a cheat wire for sampler clock synchronization and provision was made for adding variable but equal quantities of random noise or c.w. interference into the digital and analogue channels (D and A, Fig. 3): the same extraneous noise or interference could also be introduced, via an attenuator, into a third channel, C, which, for reference purposes, bypassed the h.p.c.m. system to give direct transmission between the sending and receiving terminals S and R. The sending terminal provided 625-line PAL composite colour

signals as well as standard test waveforms. The operation of the equipment was checked and adjusted if necessary before each test, using standard sawtooth, pulse-and-bar and multiburst waveforms in order to ensure optimum signal reconstruction under low-noise conditions.

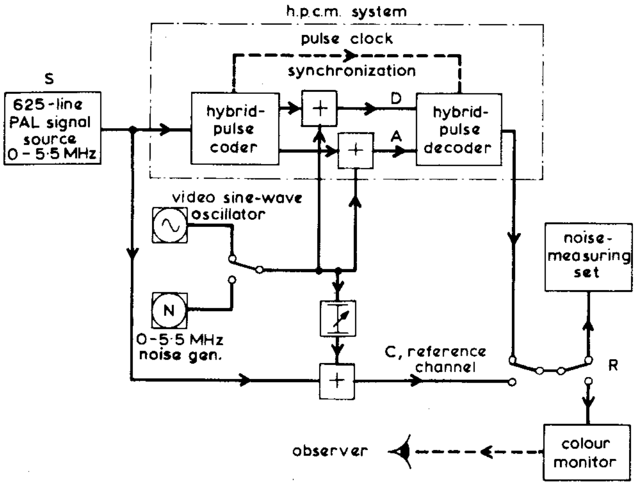

Fig. 3 - Experimental arrangement for determining the performance of twin-pulse h.p.c.m.

In a t.d.m. system the noise voltages appearing in the D and A channels at the instants of sampling would be independent of one another for true random noise. To simulate this condition the component signals in channels D and A, instead of being synchronized at the output of the hybrid coder, were allowed to be out of synchronism by about 80 ns at the points of noise insertion.

3.2. Objective Measurements and Results

The overall accuracy of waveform reconstruction with the 5-level twin-pulse system was measured on an oscilloscope using a sawtooth signal. The mean peak-peak error occurring at level transitions was about 1% (−40 dB) of peak signal at the output of the hybrid decoder; waveform reconstruction at the coder gave a figure 6 dB better than this.

Using the arrangement shown in Fig. 3 the noise improvement characteristic was determined for white random noise using a mid-grey picture signal; measurement was made both with the mid-grey level lying half-way between quantization levels and coinciding with them; there was no significant variation of results with level position over the greater part of the s.n.r. range. Fig. 4 shows the measured s.n.i. characteristic, which makes no allowance for sync pulse truncation, and also the theoretical characteristic taken from Fig. 4 of Reference 1 (m = 5) for comparison. The measured noise improvement in the analogue-limited region was 13·5 ± ·25 dB which is very close indeed to the theoretical figure of 14 dB. With 5 quantizing levels positioned as in Fig. 2 truncation of the sync pulses below level 0 will increase the actual noise improvement by some 2 dB, as previously mentioned, to about 15·5 dB. For high channel s.n.r.s the measured noise improvement falls away due to source noise and errors in waveform reconstruction. At the lower end of the characteristic the measured threshold is extended by about 3 dB, but this is probably due to the fact that the noise-measuring set which was used assumed Gaussian noise statistics rather than quantizing noise statistics to obtain r.m.s. readings from quasi-peak detection.

The noise margin of the digital channel was determined by replacing the noise source with a sine-wave oscillator (Fig. 3) and monitoring digital breakdown in the hybrid decoder using an oscilloscope. Threshold was reached 2 dB below the theoretical figure over most of the modulation range but was reduced by a further 1 or 2 dB at level transitions.

3.3. Subjective Assessment of System Performance

A number of tests were made in order to assess subjectively the performance of the hybrid-pulse-coding video system. Using the arrangement shown in Fig. 3 the subjective noise improvement was determined for white random noise and also for sine-wave interference: in addition, the picture impairments due to sampler timing and digital-analogue waveform delay errors were assessed. The residual impairment of h.p.c.m. pictures due to overall system inaccuracies in the absence of extraneous signals were deduced from these measurements.

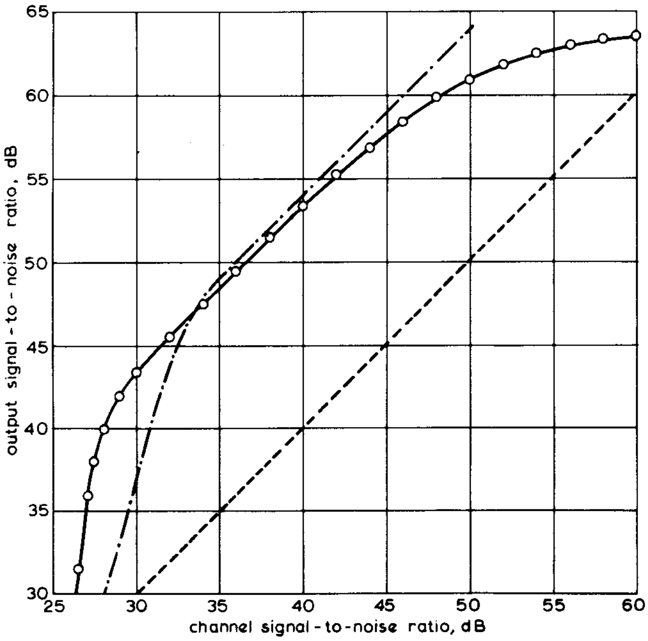

Fig. 4 - Measured noise improvement characteristic for 5-level h.p.c.m. of composite vision signals: comparison with theoretical result

—o— measured characteristic
—·— theoretical characteristic
----- zero noise improvement

Eight fairly experienced observers were chosen for the tests. The group observed a high-grade colour television monitor having a screen diagonal of 0·46 m (18 in.); the ambient illumination of the unexcited monitor screen was about 0·17 cd/m^2 (0·05 ft-L) and the displayed white brightness was about 62 cd/m^2 (18 ft-L). The observers

viewed the monitor at a distance of about six times picture height. At the start of each series of tests observers were shown an unimpaired picture followed by examples of severe impairment using the h.p.c.m. system and the reference system (direct transmission). The tests were arranged with the h.p.c.m. and reference systems operating in a mixed random order and each test was of the A, B, A type with the impaired picture sandwiched between two unimpaired reference pictures. Observers were asked to assess the perceptibility of varying degrees of impairment using the EBU standard six-point impairment scale given below.

1. Imperceptible
2. Just perceptible
3. Definitely perceptible but not disturbing
4. Somewhat objectionable
5. Definitely objectionable
6. Unusable

The picture source was a colour slide-scanner employing electronic masking and capable of producing highly saturated pictures typical of those obtained from a colour television camera. As the number of tests were necessarily restricted the choice of pictures was important. Two were chosen; the first, known as 'Ski-couple', was a highly saturated slide which demanded good waveform reconstruction at high video frequencies in order to obviate noticeable errors in saturated colours. The second slide, referred to as 'Cottages' was much less saturated and represented average colour programme material.

The subjective results for random noise interference averaged over 8 observers are shown in Fig. 5. The vertical ordinates correspond to increasing output s.n.r.s since the impairment grading scale has been inverted; this is convenient because it makes the subjective improvement characteristics similar in form to the previously described objective characteristics. The 'Ski-couple' picture (Fig. 5(*a*)) gives a maximum s.n.i. of 7 dB at an impairment grade of about 2½; on the other hand, the maximum reduction in impairment is 1½ grades at a channel s.n.r. of 37 dB. The corresponding maximum figures for the 'Cottages' picture (Fig. 5(b)) are rather higher; namely, 12 dB s.n.i. for an output impairment of 2 grades and 2 grades of improvement for a channel s.n.r. of 38 dB. Both h.p.c.m. characteristics flatten out for large channel s.n.r.s because of residual errors existing in the reconstructed pictures.

The performance of h.p.c.m. with co-channel interference was simulated by replacing the noise source in the previous test with a video sine-wave oscillator. The frequency was approximately 156·5 kHz but finely adjusted so that the diagonal interference pattern ran down the picture slowly enough to be resolved. The average subjective results are shown in Fig. 6; the impairment grading, with the scale inverted as before, is shown as a function of the peak signal-to-r.m.s. interference ratio (s.i.r.) in the channel. The signal-to-interference improvement is substantially constant over a large range of interference levels above threshold. The 'Ski-couple' picture (Fig. 6(*a*)) gives an interference improvement of 15·5 dB for output impairment grades between 2½ and 4; the maximum reduction in

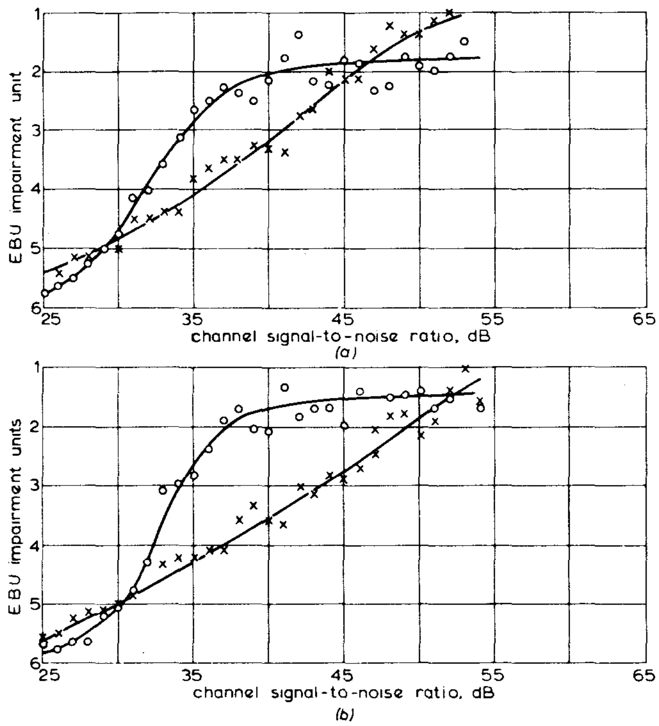

Fig. 5 - Subjective noise improvement characteristics for 5-level h.p.c.m.: random white noise

(*a*) 'Ski-couple' (*b*) 'Cottages'

—o— h.p.c.m. system —x— direct transmission

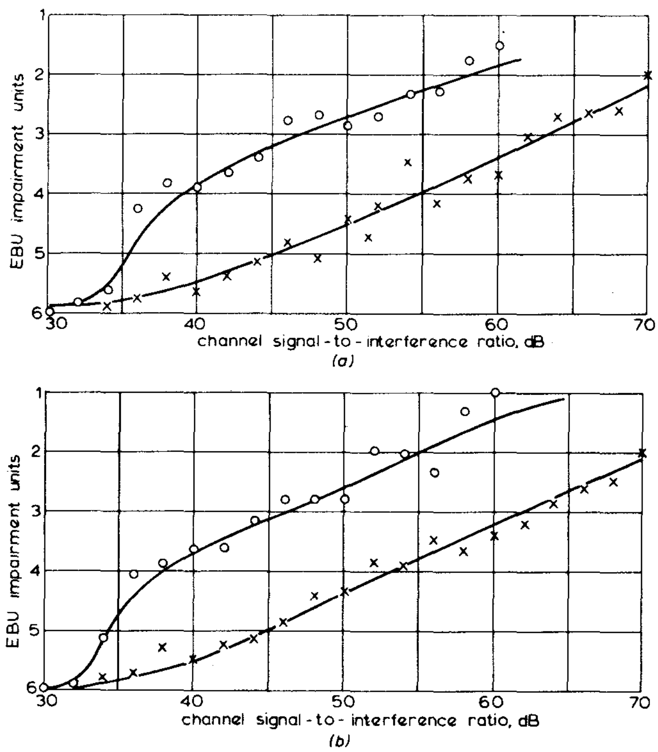

Fig. 6 - Subjective interference improvement characteristic for 5-level h.p.c.m.: sine wave interference, $f \cong 156500$ Hz

(*a*) 'Ski-couple' (*b*) 'Cottages'

—o— h.p.c.m. system —x— direct transmission

impairment is about 1¾ grades for channel s.i.r.s lying between 42 and 52 dB. The 'Cottages' picture gives almost identical results (Fig. 6(*b*)). The interference improvement is again about 15·5 dB but the corresponding impairment range is increased to 1½ to 4 grades; similarly, the maximum reduction in impairment remains at 1¾ grades but appears to hold over a 40 to 60 dB range of channel s.i.r.s.

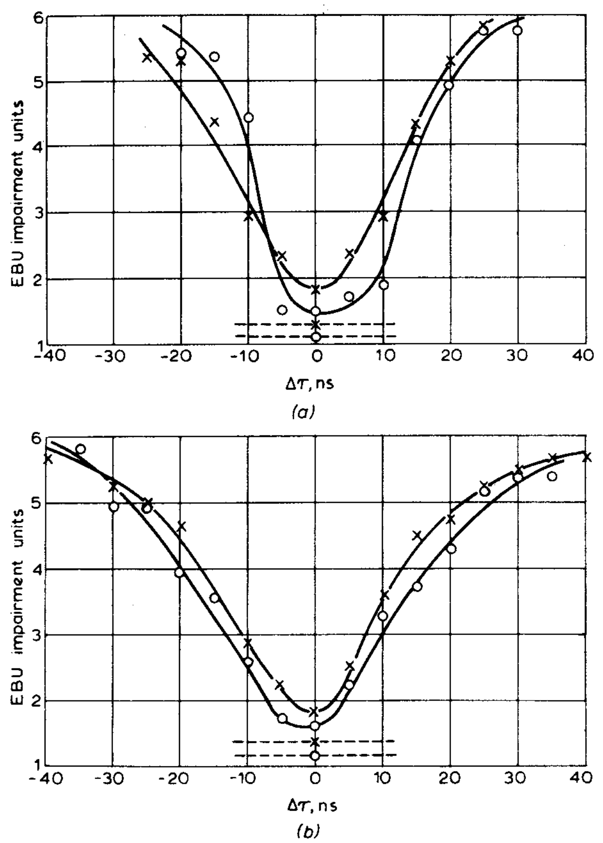

Fig. 7 - Subjective assessment of picture impairments due to synchronization errors in the hybrid decoder

(*a*) sampler clock synchronization

(*b*) digital-analogue waveform synchronization

'Ski-couple' 'Cottages'

Residual impairments

Picture impairments due to synchronization inaccuracies in the quantizer sampling circuits of the h.p.c.m. decoder and also in the addition of the digital and analogue signal components were measured subjectively by varying the pertinent delay times $\Delta\tau$ by about ±40 ns in randomly ordered steps of 5 ns. During each series of tests the observers were also asked to judge, unwittingly, the quality of unprocessed, nominally unimpaired, pictures; this was to measure the residual impairment of the system so that the net quality of properly synchronized h.p.c.m. pictures could be fairly assessed. The average results of the timing tests, for the 'Ski-couple' and 'Cottages' pictures are shown in Figs. 7(*a*) and (*b*) respectively. Both pairs of characteristics show pronounced minima and there is little difference between the results from the two pictures. The timing accuracies required in order to limit picture impairments to any particular grade are given by the curve widths corresponding to that grade. For example, if grade 3 impairment (perceptible but not disturbing) is not to be exceeded, synchronization at the quantizer (Fig. 7(*a*)) and at the point of component waveform addition (Fig. 7(*b*)) needs to be accurate to within about ±9 ns, i.e. $\pm T/10$ where $T = 1/2f_0$. The waveform slope of a $\sin x/x$ pulse band-limited to f_0 at the first pair of adjacent sampling points is $\pm 1/T$ (Reference 1, Table 2). In the extreme case, where a peak white pulse is flanked by black level, a timing displacement of $\pm T/10$ can produce a maximum amplitude error of ±10%; this corresponds to half a quantization step for the 5-level system.

The true subjective assessment of the impairment introduced by the experimental h.p.c.m. system with perfect transmission and synchronization is given by the difference between the impairment grading for $\Delta\tau = 0$ and the corresponding impairment grading for unprocessed pictures (residual impairment shown by broken horizontal lines, Fig. 7). The mean difference is about ½ grade for both the 'Ski-couple' and 'Cottages' pictures so that this represents the net subjective degradation of a 5-level h.p.c.m. colour transmission.

To summarize the results of the subjective tests, the noise improvement of the system reached the expected figure of 15·5 dB (i.e. the measured 13·5 ± ·25 dB plus 2 dB for sync pulse truncation) with c.w. interference but for random noise it fell short by 8·5 dB and 3·5 dB for saturated and unsaturated pictures respectively. Decoder synchronization was critical and timing errors had to be kept within ±9 ns for satisfactory performance; this figure is consistent with theory. The net impairment of h.p.c.m. pictures due to processing alone amounted to about ½ EBU grade.

4. CONCLUSIONS

The practical feasibility of hybrid coding a 625-line video signal into a bandwidth of 11 MHz has been tested with experimental equipment which provided two simultaneous 5·5 MHz channels for the 5-level digital and the analogue components; a third circuit was used for clock synchronization. The synchronizing waveform was coarsely quantized by truncating the composite signal by about 2 dB thus increasing the theoretical noise improvement from 14 to about 16 dB.

The objective noise measurements gave results within about 0·5 dB of the theoretical figure but the subjective tests revealed further instrumental errors whose subjective magnitude depended on the nature of the noise and the picture signal colour saturation. Although with c.w. interference, the results were in excellent agreement with theory, the subjective noise improvement with random channel noise was some 4 to 8 dB below the expected figure; the worst result was obtained with saturated pictures.

The relatively low performance obtained with random noise was due to instrumental limitations in the threshold detectors of the hybrid decoder. The effect of these limita-

tions is more pronounced with noise than with c.w. interference because of the random distribution of the former; with random noise of fixed power, the digital error rate rises very steeply with decreasing detector noise margin. Although coder synchronization was critical the subjective performance in this respect was quite consistent with theoretical prediction.

Very careful adjustment of the experimental equipment could not entirely remove processing errors, which were just noticeable in the output pictures. It is estimated that the reconstruction errors at the hybrid decoder would have to be reduced by a further 6 dB in order to render them imperceptible; this would also improve the subjective noise performance since it is at fast level transitions due to large subcarrier amplitudes where digital errors are most likely to occur. Performance in respect of c.w. interference is excellent although in practice r.f. channels are unlikely to provide adequate equalization stability unless some form of adaptive equalization is employed.

The experiments have confirmed the practical feasibility of hybrid-coding for video circuits but they have also underlined the rather stringent requirements imposed on on the instrumentation and channel parameters.

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